INVESTIGATION OF ULTRAVIOLET INTERSTELLAR EXTINCTION

Grant NGR 09-015-200

Final Report

For the period 1 October 1972 to 30 June 1973

Principal Investigators

Dr. Cecilia Payne-Gaposchkin
Mrs. Katherine L. Haramundanis

Prepared for

National Aeronautics and Space Administration
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ABSTRACT

In Semiannual Progress Report No. 1, for the period 1 October 1972 to 31 March 1973, we described in some detail the investigations and results of that period. Early results are summarized in final form below, together with the investigations of the last three months, 1 April to 30 June 1973.

Most of our results concern interstellar extinction in the ultraviolet. These results were initially obtained by using data from main-sequence stars and were extended to include supergiants and emission stars. The principal finding of our analysis of ultraviolet extinction is not only that it is wavelength dependent, but that it changes with galactic longitude in the U3 passband (λ_{eff} = 1621 Å); it does not change significantly in the U2 passband (λ_{eff} = 2308 Å). Where data are available in the U4 passband (λ_{eff} = 1537 Å), they confirm the rapid rise of extinction in the ultraviolet found by other investigators. However, in all cases, emission stars must be used with great caution. It is important to realize that while extinction continues to rise toward shorter wavelengths in the ultraviolet, including the shortest ultraviolet wavelengths heretofore measured (1100 Å), it no longer plays an important role in the x-ray region (50 Å). Observations in the gap are solely needed.

An investigation of ultraviolet extinction as a function of distance is essential to our understanding of the interstellar medium, since it appears possible to separate the effects of particle size and composition with the existing data. For this purpose, we have obtained the absolute ultraviolet magnitudes of stars on the main sequence by two methods. Distances of individual stars can thus be determined from both ultraviolet and visual data.

Several subsidiary investigations have been prompted by our findings. In Orion, it is clear that the correlation of $E(\lambda-V)/E(B-V)$ disintegrates; on the basis of available radial-velocity data, we suggest that this occurs because of the existence of unsuspected multiples among the stars observed. A program to obtain radial velocities for all these stars would be a direct test of our hypothesis; Dr. R. Schild of Smithsonian Astrophysical

Observatory is willing to take the requisite spectra for this investigation. It is also possible that the noncorrelation is caused by scattering directly into the line of sight by specially aligned particles. This can be tested by using the observed polarization measures for these stars in the visual, but would best be done by obtaining polarization measures in the ultraviolet.

A comparison of our observed intrinsic colors with those predicted by blanketed theoretical model atmospheres demonstrated that while agreement for B stars is excellent, that for stars later than A0 is poor. The sense of the disagreement is that the observed intrinsic colors for late-type stars are too red; i.e., the stars are too faint in the ultraviolet.

The derived color excesses in the ultraviolet suggested two further large-scale investigations: 1) An analysis of HD spectral classifications demonstrated that systematic errors exist in this catalog as a function of spectral class and apparent visual magnitude. The maximum error occurs for B9 stars, which at 10th magnitude have the color of a B3 star in (B-V). 2) An analysis of the systematic errors of the Photoelectric Catalogue showed that systematic errors amounting to 0.03 in magnitude or color afflict 20% of the sources in the compilation we have examined.

Several individual objects for which ultraviolet fluxes have been observed or estimated are of additional interest: 30 Doradus (the Tarantula Nebula), the Crab Nebula, Jupiter, and two small clusters discovered by Celescope. 30 Doradus is the prototype of objects that are bright in the passband containing Lyman α; the Crab Nebula is fainter in the ultraviolet than is expected from its synchrotron emission. Jupiter's brightness at 1621 Å implies a new model for its atmosphere. The two small clusters are potentially very young and are situated on the opposite edges of a dark nebula in Cassiopeia.

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1. INTERSTELLAR EXTINCTION IN THE ULTRAVIOLET

1.1 The Wavelength Dependence of Extinction

The Celescope Experiment, on board the Orbiting Astronomical Observatory-2 (OAO-2) investigated ultraviolet extinction utilizing data in four ultraviolet passbands (Table 1) (Davis, Deutschman, and Haramundanis, 1973). During this investigation, it was necessary first to obtain the intrinsic colors for the spectral range observed.

Table 1. The Celescope passbands.

Passband	λ_{eff}	Bandwidth
U1	2582	550
U2	2308	850
U3	1621	325
U4	1537	450

This was done for B stars by determining the intrinsic colors $(B-V)_0$ for each star by means of Johnson's (1958) Q method. For stars later than A0, MK spectral classifications and the relation of Johnson (1963) were utilized. The criterion for an unreddened star was established by a statistical analysis of the standard deviations characteristic of UBV photometry published in the Naval Observatory Photoelectric Catalogue (Blanco, Demers, Douglass, and Fitzgerald, 1968). Only stars that have MK spectral classifications and are unreddened according to the established criterion $[E(B-V) \leq 0.04]$ were used to derive intrinsic ultraviolet colors. The relation of

$(Ui - V)_0$ to $(B - V)_0$ was determined by least squares for B stars and graphically for later type stars (Haramundanis and Payne-Gaposchkin, 1973) (Table 2).

Table 2. Observed intrinsic ultraviolet colors $(Ui - V)_0$ for luminosities IV and V.

Spectral class	$(B - V)_0$	$(U1 - V)_0$*	$(U2 - V)_0$	$(U3 - V)_0$	$(U4 - V)_0$
B0	-0.30	1.60	0.674	0.367	0.044
B0.5	-0.28	1.79	0.836	0.582	0.307
B1	-0.26	1.98	1.016	0.820	0.600
B2	-0.24	2.17	1.196	1.058	0.893
B3	-0.20	2.55	1.555	1.534	1.478
B4	-0.18	2.74	1.735	1.773	1.771
B5	-0.16	2.93	1.915	2.011	2.064
B6	-0.14	3.12	2.095	2.249	2.356
B7	-0.12	3.31	2.275	2.487	2.649
B8	-0.09	3.59	2.545	2.844	3.088
B9	-0.06	3.87	2.815	3.202	3.527
B9.5	-0.03	4.15	3.085	3.559	3.966
A0	0.000	4.43	3.358	4.15	4.41
A1	0.02	4.46	3.55	4.40	4.65
A4	0.11	4.60	4.11	5.50	
A7	0.21	5.30	4.60	6.80	
F0	0.32	5.46	5.10	8.20	
F3	0.40	5.50	5.45		
F7	0.50	5.85	5.82		
G1	0.60	6.48	6.15		
G3	0.65	6.79	6.35		

*Camera 1 only.

With a standard sequence of ultraviolet colors, the color excess for each observed star was obtained. Most of the Celescope data were observed in the U2 and U3 passbands; U1 observations were restricted because of a rapidly deteriorating magnitude

limit, and those in U4, because of the bright background from the geocorona. With use of the color excesses, it was possible to verify directly the wavelength of extinction in the ultraviolet found by Bless and Savage (1972) and others. By taking data for which $E(B-V) \leq 0.14$, the averages of $E(m_\lambda - V)/E(B-V)$ at low galactic latitudes and their standard deviations are as follows:

Passband	λ_{eff} (Å)	$1/\lambda$ (μ^{-1})	$E(m_\lambda - V)/E(B-V)$
U2	2308	4.33	3.47 ± 1.16
U3	1621	6.16	4.33 ± 1.49
U4	1537	6.51	4.56 ± 2.73

The averages at high latitudes ($|b^{II}| \geq \pm 5°$) do not differ significantly from those at low latitudes, but the standard deviation at high latitudes is always larger. There are insufficient data in the U1 passband to obtain a meaningful average. The averages are compared with the mean relation of Bless and Savage in Figure 1.

1.2 Extinction as a Function of Galactic Longitude

The average values of the color-excess ratio in each passband were used to test the color-excess ratios for individual stars against a possible correlation with galactic longitude. Only in the U3 passband was a significant variation in the color-excess ratio with galactic longitude found. The variation is shown in Figure 2; maxima occur in the regions of Carina and Cygnus. It should be noted that in the direction of 30° near the galactic center, where no observations are recorded, several dozen exposures were taken by the Celescope Experiment. The gap indicated in this direction on the diagram is thus probably a real one, and the color excesses there may be exceptionally large.

Although the variation in the color-excess ratio in the U3 passband appears real, its interpretation is subject to the usual ambiguities. If the assumption is made that the composition of the interstellar medium is the same everywhere, then the observed variation is a clear indication of differences in particle size. If this is the case, then

the observed maxima indicate that in the region of Carina and Cygnus, small particles predominate, while toward the galactic center and toward Puppis, larger particles preponderate.

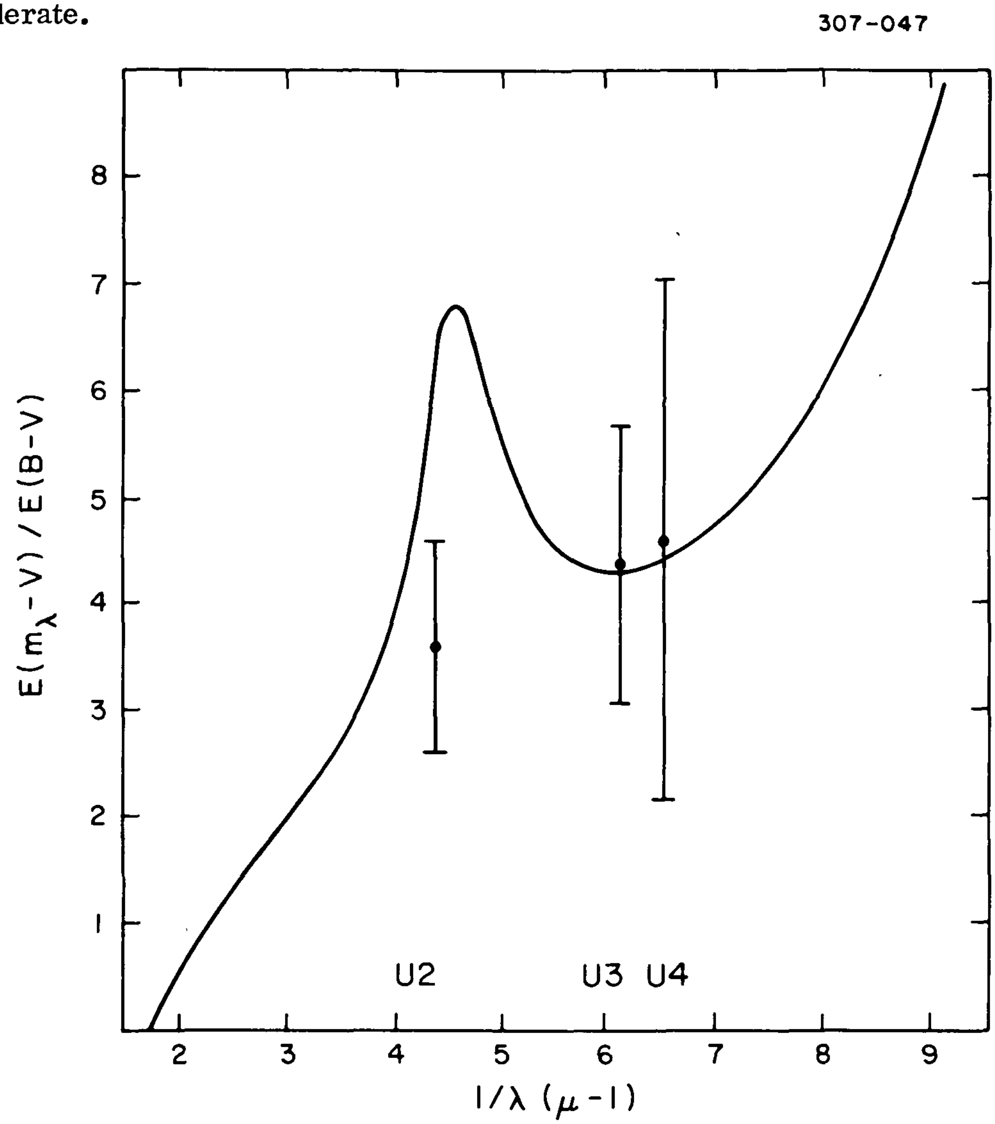

Figure 1. The wavelength dependence of the ultraviolet-to-visual color-excess ratios. The solid curve is the relation of Bless and Savage (1972) obtained from spectral scans; the points are the averaged ratios for the Celescope passbands at low galactic latitudes ($|b^{II}| \leq \pm 5°$). Data in the U1 passband are too few to give a meaningful average. Error bars represent ±1 standard deviation.

1.3 Extinction as a Function of Distance from the Sun

By utilizing the stars for which MK classifications and UBV photometry are available, it has been possible to obtain the distribution of stars observed by the Celescope Experiment with distance from the sun (Figure 3). In the direction of Carina–Vela,

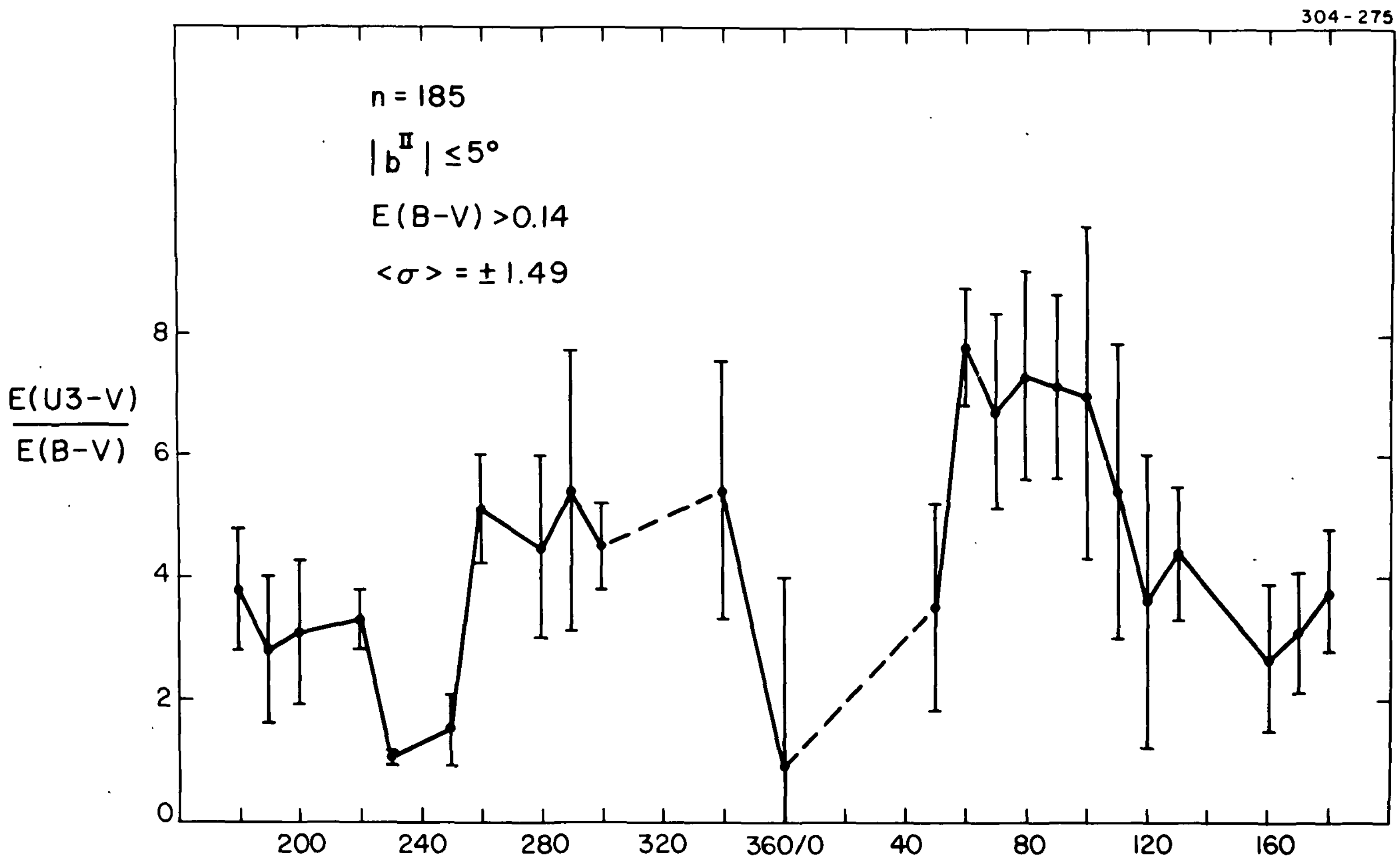

Figure 2. The longitude dependence of the color-excess ratio in the U3 passband. Error bars represent ±1 standard deviation.

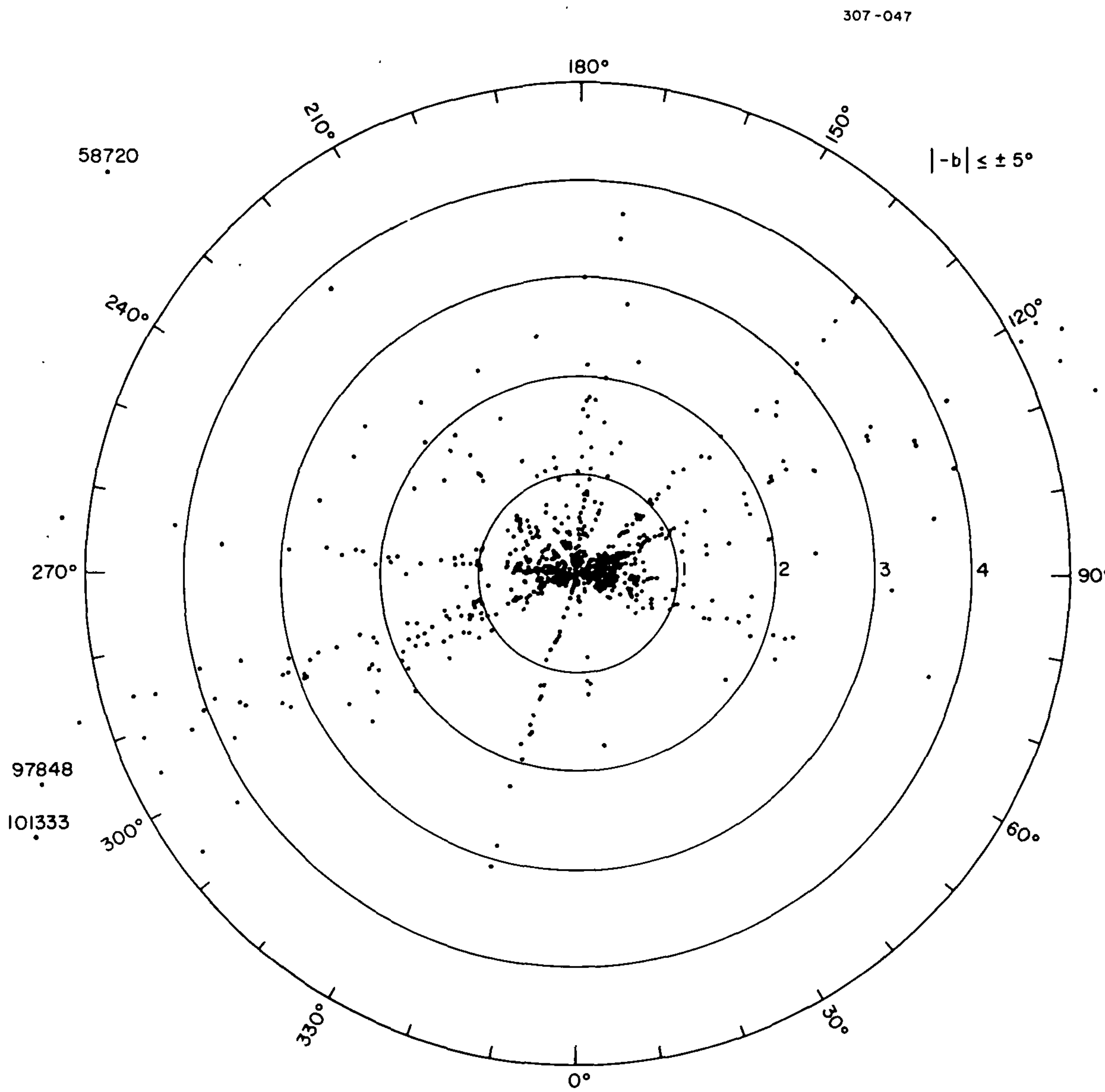

Figure 3. The distribution of stars observed by Celescope at low galactic latitudes ($|b^{II}| \leq \pm 5°$) derived by using UBV photometry, the absolute magnitudes of Blaauw (1963), and the ratio of general to selective absorption of 3.0.

stars are observed out to 5 kpc; toward Cygnus and Cassiopeia, stars are also seen at great distances. Toward the galactic center, observations cease at less than 2 kpc, and in the direction of the anticenter, they are found to almost 4 kpc. The apparent distribution of these stars does not, however, appear to give a very clear picture of galactic structure, even when the stars selected are all earlier than type B3. The best correlation with structure can be seen in diagrams where distances are determined on the basis of cluster membership (see Schmidt-Kaler, 1970). An examination of the Celescope stars common to the clusters given in Becker and Fenkart (1971) reveals that a few stars may be so identified. These would be the first to be utilized in a discussion of extinction as a function of distance.

Absolute visual magnitudes have been established (Blaauw, 1963) as a function of spectral type and luminosity. Parallaxes are additionally known for 320 of the stars observed by Celescope. By using each of these parameters independently, it has been possible to establish for main-sequence stars (luminosity class V) the relation of spectral class and absolute ultraviolet magnitude. The parallax determinations are suitable for obtaining absolute magnitude for stars out to about 200 pc. At greater distances, the known absolute visual magnitudes, the apparent visual magnitudes, and the ratio of general to selective absorption of 3.0 were used to obtain the distance of each star for which the spectral and luminosity class were known. With the distance determined, the ultraviolet absolute magnitude could be computed. The results are given in Table 3. The distances computed on the basis of the data available were compared with those obtained by Lesh (1972), who used similar ground-based data, and by Walborn (1971), who classified a number of OB stars using spectrograms at 63 Å mm^{-1}. Lesh has treated her data somewhat differently than we have, and her distances tend to be significantly larger than ours. Agreement between our distances and those of Walborn is excellent; we attribute this to the great care he has taken in his classifications.

With the ultraviolet absolute magnitudes, it will be possible to obtain the distances of many stars observed by Celescope and to verify the distances based on photometry with those obtained from galactic clusters. Once we have well-calibrated distances, we can establish whether ultraviolet extinction changes with distance as well as with direction.

Table 3. Absolute ultraviolet magnitudes (luminosity class V).*

Spectral class	M_{U1}	M_{U2}	M_{U3}	M_{U4}	$(B-V)_0$	M_V
B0	-6.40	-7.16	-7.42	-7.69	-0.30	-4.4
B1	-5.22	-6.18	-6.38	-6.60	-0.26	-3.6
B2	-3.93	-4.90	-5.04	-5.21	-0.24	-2.5
B3	-2.75	-3.74	-3.77	-3.82	-0.20	-1.7
B4	-2.21	-3.21	-3.18	-3.18	-0.18	-1.35
B5	-1.67	-2.68	-2.59	-2.54	-0.16	-1.0
B6	-1.18	-2.20	-2.05	-1.94	-0.14	-0.7
B7	-0.69	-1.72	-1.51	-1.35	-0.12	-0.4
B8	+0.09	-0.95	-0.66	-0.41	-0.09	+0.1
B9	+0.87	-0.18	+0.22	+0.53	-0.06	+0.6
A0	+1.83	+0.76	+1.55	+1.81	0.00	+1.0
A1	+2.36	+1.45	+2.30	+2.55	0.02	+1.5
A2	+2.49	+1.72	+2.64		0.05	+1.2
A3	+2.62	+1.99	+2.98		0.08	+1.5
A4	+2.75	+2.26	+3.65		0.11	+1.75
A5	+3.07	+2.51	+4.04		0.15	+1.8
A6	+3.39	+2.76	+4.43		0.18	+1.90
A7	+3.70	+3.00	+5.20		0.21	+2.0
A8	+3.89	+3.30	+5.80		0.24	+2.10
A9	+4.08	+4.10	+6.40		0.27	+2.25
F0	+4.26	+3.90	+7.00		0.32	+2.4
F1	+4.45	+4.19			0.35	+2.60
F2	+4.64	+4.48			0.38	+2.8
F3	+4.83	+4.78			0.40	+2.93
F4	+5.12	+5.08			0.42	+3.06
F5	+5.41	+5.38			0.44	+3.2
F6	+5.70	+5.68			0.47	+3.5
F7	+6.00	+5.97			0.50	+3.75
F8	+6.36	+6.25			0.53	+4.0
F9	+6.72	+6.53			0.56	+4.20
G0	+7.08	+6.81			0.58	+4.4
G1	+7.43	+7.10			0.60	+4.55
G2	+7.79	+7.34			0.625	+4.7
G3	+8.02	+7.58			0.65	+4.83

*$M_{Ui} = (Ui - V)_0 - 3.60 + M_V$, where -3.60 represents the correction to rectify Celescope units (w m^{-2} m^{-1}) to those of the UBV system (ergs sec^{-1} cm^{-2} $Å^{-1}$); M_V is the absolute visual magnitude, taken from the calibration of Blaauw (1963, p. 401); and i = 1 to 4, the Celescope passbands.

1.4 Extinction for Emission Stars

It has been established (Bless and Savage, 1972; Code and Savage, 1972) that extinction in the ultraviolet is not, on the average, the same for both stars in the Be category and B stars with no emission lines. Coyne (1972) showed that the cause of apparent high extinction ratios for these stars is emission from the Balmer continuum, which contributes significantly to the ultraviolet fluxes of such stars. This is sufficient cause to exclude Be stars when studying extinction in the ultraviolet.

A statistical study of the O stars observed by the Celescope Experiment (Haramundanis, 1973a) demonstrated conclusively that normal O stars and emission O stars (those classified as Of) do not, on the average, have the same color-excess ratios. The explanation advanced to explain this phenomenon in the Be stars does not seem applicable to the O stars. Walborn (1971) suggested that the emission characteristics seen in Of stars may be indicative of a luminosity difference between these stars and the absorption O stars. This appears to agree with their observed ultraviolet color excesses, and further indicates that emission O stars should be used for studying interstellar extinction only with considerable caution.

1.5 Extinction in the Ultraviolet versus Polarization in the Visual

The polarization of starlight is an important observational parameter in any analysis of the interstellar medium, for it is believed that the amount of polarization may indicate the degree of alignment of the particles that comprise the medium. To some extent, the amount of polarization is known to be correlated with galactic longitude; this correlation seems to be more in evidence when nearby stars are excluded. If polarization is indicative of the alignment of particles in the medium, theoretical extinction curves must take into account particles that are asymmetrical and able to be aligned by the available forces.

Hiltner (1951) measured polarization in the visual for a large number of stars, many of which were observed by the Celescope Experiment. By means of his data and the Celescope color excesses, it has been possible to establish that the percentage of polarization in the visual is correlated with the color excess in the U2 passband,

exclusive of emission stars (Figure 4). There is no such correlation in the U3 passband. In the U1 and U4 passbands, there are too few data for an adequate analysis. The implication of this observed fact is that particles that contribute most markedly to the extinction curve at 2300 Å are aligned, but that those that contribute most significantly at 1600 Å are not.

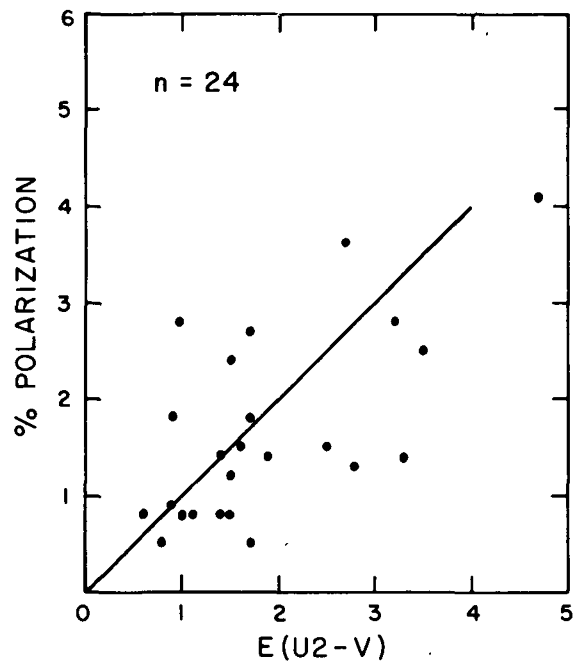

Figure 4. The correlation of percentage of polarization and color excess in the U2 passband. Polarization data were taken from Hiltner (1951).

At present, there are insufficient data on polarization in the ultraviolet to investigate this question further. Such data would be invaluable in settling the question of particle size and composition of the dust grains that cause the observed extinction and polarization. Further data on visual polarization in the Southern Hemisphere are definitely needed.

1.6 Conclusions

Extinction in the ultraviolet is not only wavelength dependent and of a form suggestive of graphite, but also, at the wavelength 1600 Å ($1/\lambda = 6.16\ \mu^{-1}$), longitude

dependent. If it is assumed that the composition of the interstellar medium is everywhere the same, the ultraviolet observations strongly suggest that particle sizes toward the galactic center are relatively large, while in the direction of Carina–Vela and Cygnus they are, on the average, small. Wherever possible, extinction curves should not be deduced from emission stars, even those of spectral class O.

The correlation between the amount of visual polarization and ultraviolet extinction at 2300 Å implies that the particles that contribute to the rise of extinction at this wavelength tend to be aligned, while those that contribute to the longitude variation of extinction at 1600 Å do not. Observations of polarization in the ultraviolet would be invaluable in probing these questions and establishing firmly if the assumption of uniform composition is tenable.

2. SUBSIDIARY INVESTIGATIONS WITH THE ULTRAVIOLET DATA

2.1 The Noncorrelation of $E(\lambda - V)/E(B - V)$ in Orion

During the examination of the slopes of the reddening lines at high galactic latitudes, it became evident that the usual correlation of $E(\lambda - V)/E(B - V)$ did not pertain in the region of Orion ($200° \leq \ell^{II} \leq 210°$, $-10° \leq b^{II} \leq -20°$). The noncorrelation is particularly striking in the U2 passband ($\lambda_{eff} = 2308$ Å) but is also present in the U3 passband. This phenomenon is caused by two factors: the presence (in the U2 passband) of 25 stars with large negative color excesses in the ultraviolet, and a range of 3 magnitudes in ultraviolet color excess with a corresponding range of only 0.2 in $E(B - V)$.

An examination of the available radial velocities for the observed stars indicates further that a significant number of them are variable. In several cases, the spectral class and $(B - V)$ color do not coincide (Sharpless, 1952). We suggest that these facts imply that many of the stars in the region are unresolved multiples and the apparent anomalies are intrinsic to the stars. The ultraviolet color excesses support this. An observational test of this would be to obtain radial velocities of all the stars in the area and determine if they are variable. Dr. R. Schild of Smithsonian Astrophysical Observatory is prepared to take 40 Å mm^{-1} spectra for this purpose.

It would also be valuable to examine the color excesses of the Orion stars and their observed polarization. If the correlation of color excess with polarization in the U2 passband also pertains in Orion, it would indicate that a significant contribution to the ultraviolet fluxes of these stars is induced by scattering of ultraviolet light into the line of sight along aligned particles.

2.2 Comparison of Observed and Predicted Ultraviolet Colors

As a check on the observed ultraviolet intrinsic colors, a comparison was made with the ultraviolet colors predicted by line-blanketed model atmospheres (Kurucz, Peytremann, and Avrett, 1973). For B stars, the agreement between theory and

observation is excellent (Haramundanis and Payne-Gaposchkin, 1973), but that for stars later than A0 is less satisfactory. Theoretical colors appear to be too bright to coincide well with the observed colors. Since the comparison was made exclusively on the basis of unreddened stars [E(B - V) ≤ 0.04], it seems unlikely that the observed fluxes are too faint because the stars are heavily reddened. Most probably, the theoretical fluxes have not been sufficiently modified in the ultraviolet by the atomic lines employed in the predictions.

2.3 The Intrinsic Colors of Wolf-Rayet Stars

Wolf-Rayet stars are of considerable interest in studies of extinction because of their great luminosity and distance. However, since most of these stars are binaries, the derivation of their intrinsic colors is a matter of much difficulty. Among the stars observed by Celescope, 14 were classified as Wolf-Rayet stars. By use of available data, it has been possible to obtain preliminary colors for these stars in the ultraviolet. In an analysis of UBV data for 11 Wolf-Rayet stars, Smith (1968) obtained an intrinsic (B - V) color of -0.08, subject to considerable uncertainty. Our analysis suggests a (B - V) color of about -0.18. The ultraviolet colors for class WN are $(U2 - V)_0 = 2.0 \pm 0.3$ and $(U3 - V)_0 = 2.2 \pm 0.3$. A more complete analysis of this class of stars utilizing spectral scans when available is clearly indicated.

2.4 The Intrinsic Colors of Supergiants

Supergiants are of great potential interest because at high luminosity they are seen to exceptionally great distances in the Galaxy. By using the colors of Serkowski (1963), we derived their ultraviolet colors by examining the relation of $(B - V)_0$. Objects of high rotational velocity, although predicted (Furenlid, 1970; Collins, 1965) to be unusually bright in the ultraviolet, do not appear to be different from objects of low velocity. They have thus not been eliminated from this set of data. In almost all cases, however, emission stars are anomalous, particularly in the U2 passband, and have been excluded from the analyses described here. The ultraviolet colors of supergiants do not differ significantly from those of main-sequence stars when the relations are compared on the basis of intrinsic (B - V) color, rather than on the basis

of spectral class. This similarity does not hold if the colors of Johnson (1963) are used for supergiants. Using filter photometry for 16 stars observed by the Wisconsin Experiment on board OAO-2, Laget (1973) has discussed the slope of the reddening line. His conclusion that the reddening law for supergiants differs from that for main-sequence stars depends critically on the $(B-V)_0$ colors that he has adopted for supergiants. Our analysis shows that the reddening law for supergiants is not significantly different from that for main-sequence stars.

2.5 Comparison of Wisconsin and Celescope Ultraviolet Data

It has been possible to make two comparisons utilizing Celescope and Wisconsin ultraviolet data. The importance of these comparisons rests in the fact that neither experiment has been calibrated absolutely. The Celescope experimental data have furthermore been compared with theoretical predictions. Two kinds of data are available from the Wisconsin Experiment: filter photometry in a sequence of broad passbands from 1430 to 4250 Å, and photometric scans in the wavelength range 1050 to 3600 Å. Celescope filter photometry is available in four broad passbands from 1500 to 2600 Å.

Celescope filter photometry and Wisconsin spectral scans were compared by utilizing Celescope colors and the scans of Bless and Savage (1972). Six stars were common to both sets of observations. However, of the six, three are binary or multiple and the other three are emission stars. All these stars are therefore difficult to compare with Celescope observed colors because of the differences of angular resolution of the two instruments and the intrinsic difficulty encountered when interpreting the spectral scans of emission stars (Coyne, 1972; Haramundanis, 1973a).

The Wisconsin scans were prepared in the usual manner by the direct comparison of a reddened and an unreddened star. To compare the data in these scans with Celescope filter photometry, values at 50 Å intervals were read from the published curves and a single value obtained for each star and passband by integration over the interval appropriate to each, taking into account the spectral sensitivity of each Celescope passband. Owing to the resolution of the Celescope system and to insufficient knowledge about the fainter components of the three multiple systems, the comparison has been made only with the three emission stars (see Table 4). The

color-excess ratios, Celescope and Wisconsin, agree within the error of observation. A standard error for each ratio was determined from the known errors of ground-based and ultraviolet photometry and from the known problems of setting the zero point of the Celescope system (Haramundanis and Payne-Gaposchkin, 1973). This comparison is applicable only to the very early-type stars owing to a lack of published spectral scans for later type stars.

Table 4. Comparison of Celescope filter photometry and Wisconsin spectral scans for three emission stars.

HD number	Spectral class	$\frac{E(U2-V)}{E(B-V)}$	$\frac{E(m_1-V)}{E(B-V)}$	$\frac{E(U3-V)}{E(B-V)}$	$\frac{E(m_2-V)}{E(B-V)}$
24912	O7f	3.7 ± 0.8	4.6 ± 0.6	5.1 ± 1.2	4.1 ± 0.8
41117	B2I (e?)	4.8 ± 0.8	3.5 ± 0.5		
2.0839	O6f	5.2 ± 0.9	5.0 ± 0.2		

Wisconsin and Celescope filter photometry were compared by using the intrinsic colors derivable from the data of Bless and Savage (1972) and Doherty (1972). In the range $-0.31 \leq (B-V)_0 \leq 0.0$, the comparison is made between the Wisconsin data at 1700 Å and the Celescope data at 1600 Å; and in the range $0.0 \leq (B-V)_0 \leq 1.20$, between the Wisconsin data at 2460 Å and the Celescope data at 2300 Å (see Table 5). The unreddened colors of the two data sets agree particularly well for late-type stars and, in all cases, agree within the error of observation and the error imposed by the known uncertainty of the zero-point settings of the two systems. A systematic trend between the two systems is greatest for the B stars, diminishing steadily toward the later type stars.

Table 5. Comparison of Celescope and Wisconsin filter photometry (see text).

Spectral class	$(B-V)_0$	Celescope photometry $(U2-V)_0$	$(U3-V)_0$	Wisconsin photometry (1700 - V)	(2460 - V)	Cel - Wis
B0	-0.30	-3.2±0.9		-3.9		0.7
B3	-0.20	-2.1		-2.6		0.5
B8	-0.09	-0.8		-1.2		0.4
A0	0.00		-0.2±0.3		0.0	0.2
A4	0.11		0.5		0.6	0.1
A7	0.21		1.0		1.0	0.0
F0	0.32		1.4		1.6	-0.2
F3	0.40		1.8		1.8	0.0
F7	0.50		2.2		2.6	-0.4
G1	0.60		2.6		2.8	-0.2

3. INVESTIGATIONS OF GROUND-BASED DATA PROMPTED BY ULTRAVIOLET COLOR EXCESSES

3.1 Systematic Errors of HD Spectral Classification

Once the ultraviolet color excesses for stars observed by Celescope were established, it was immediately apparent that the negative color excesses were most common in two classes of stars – those with HD spectral classifications and F stars.

In examining the stars with HD spectral classifications, it proved possible to evaluate the systematic errors of these classifications without recourse to the ultraviolet photometry. This was done in two ways: the HD and MK classifications were compared star by star, and the (B - V) colors and apparent magnitudes of stars in each class were analyzed for correlations. The first examination verified the systematic error between the HD and MK systems that had been found earlier by Houk (1973) and Schild and Chaffee (1972). The second established that HD classifications contain systematic errors that are a function of apparent visual magnitude and amount to changes as large as 6 subclasses. A 10th-magnitude star classed as B9, for example, is, in fact, probably a B3 star. The tendency is toward earlier classes for faint B stars and later classes for faint A and F stars.

The explanation for this error appears to lie in the method used by Miss Cannon in her classification of stars contained in the HD. While she could still see the lines characteristic of each class, her classifications were uniformly consistent. As the images she examined became fainter, she began classifying on the basis of the appearance of the continuum alone. This continuum was increasingly modified by the presence of the interstellar medium for fainter stars, and this was sufficient to cause the systematic trend in classifications.

3.2 Systematic Errors of UBV Photometry

In establishing intrinsic colors, it was important to develop a criterion for an unreddened star, since only unreddened stars can be used with certainty for such a derivation. The criterion was obtained by estimating the standard error for those stars with multiple entries in the Photoelectric Catalogue (Blanco et al., 1968). It was also important to determine if systematic errors existed between the sources in the catalog. An analysis was therefore made of all stars for which multiple entries occurred, and among these stars, every source that had at least 30 entries was analyzed for systematic errors. The nonparametric run test (Dixon and Massey, 1969) was used to test the deviation of entries from the mean as a function of magnitude. Data have been accumulated to test correlations against color and location on the celestial sphere, but they have not yet been definitively analyzed. The systematic errors found for 20% of the references studied are correlated with the standard errors found by Fitzgerald (1973) in his analysis of this same catalog. However, he did not examine the data for systematic errors.

The average systematic error is 0.03 in either color, (U - B) or (B - V). The errors for a particular source in both these parameters are usually correlated, and they are probably induced by slight differences either in the filters or instruments used or in the techniques for reduction of such observations. An examination of a random sample of the primary source material from which the catalog was compiled revealed that, in most cases, insufficient information is given to isolate the cause of such deviations.

The result indicates that when UBV data are taken from more than one primary source, considerable care must be used to extract the full accuracy of the data. Systematic differences between sources can produce considerable scatter in the results. A systematic error of 0.03 in the UBV colors of source A, added to an error of similar magnitude in the colors of source B, will induce an error of 0.02 in the intrinsic $(B - V)_0$ color when deduced by the Q method, an error of 0.05 in the (B - V) color excess, and an error that may be as great as 2.0 in the color-excess ratios derived by using ultraviolet data, $E(m_\lambda - V)/E(B - V)$.

4. OBJECTS OF INTRINSIC INTEREST

4.1 30 Doradus, the Tarantula Nebula

This object in the Large Magellanic Cloud appears very prominently in the U4 passband (λ_{eff} = 1537 Å), with an exposure short enough to exclude the bright background in this passband contributed by the geocorona. 30 Doradus is a dense knot of perhaps 200 O and B stars and is naturally bright in the ultraviolet. A preliminary analysis indicates that it is considerably fainter than expected. A more complete analysis and comparison with the characteristics of this object at other wavelengths would be profitable.

4.2 The Crab Nebula

The Crab Nebula is one of the most extraordinary objects in the sky, and according to the currently accepted theory of synchrotron-Compton emission (Shklovsky, 1953; Woltjer, 1957), which has been advanced to explain the mechanism that drives the Crab pulsar and illuminates the Nebula, it should emit strongly in the ultraviolet.

During the first four months of operation of the Celescope Experiment (to 27 March 1969), 26 exposures were taken in the direction of the Crab Nebula. Close to the end of the lifetime of the experiment, another series of 12 exposures was made in the same direction. In none of these exposures was any signal detected from the Crab Nebula.

In the early sequence, when the limiting magnitude of the instruments had dropped by approximately 2.6 magnitudes, two exceptionally long exposures were taken (see Table 6). From these exposures, from the known sensitivity function of the Celescope photometers (Davis, 1962, 1968), and from the amount of absorption between us and the Nebula (Miller, 1973), it is possible to set an upper limit to the brightness of the Crab Nebula in the ultraviolet. The preliminary result derived from the known parameters is that the Nebula emits at least 40 times less radiation in the ultraviolet at 2308 Å than is expected from its optical emission and the accepted theory of its

radiation. This is in agreement with the finding of Johnson (1972), who utilized Wisconsin data in an analysis of the Nebula; but his data are subject to uncertainty because of his method of bringing the ultraviolet and x-ray data, which he used for normalizing, into coincidence. Theories that attempt to explain the radiation of the Nebula must take this lack of ultraviolet emission into account.

Table 6. Celescope exposures in the direction of the Crab Nebula.

Contact	Date (1969)	UT	Nebula sought in filter	With exposure time of (sec)
S1377	12 March	04^h13^m40	2 1 4	15
			2 1 4	5
			2 1 4	15
O1381	13 March	10 45 43	2 1 4	60
			2 1 4	30
O1382	13 March	12 31 29	1 2 4	60
			2 1 3	30
			2 1 3	15
M1588	27 March	20 53 09	2	182
S1591	28 March	01 40 20	2	280

4.3 Comet Tago-Sato-Kosaka (1969g)

Three Celescope contacts were devoted to taking pictures of this comet, one of 5-sec exposure time and two of 16. The ultraviolet image of the comet in the 5-sec exposure has been analyzed to determine the size of its Lyman α halo and of its nucleus. In the U3 passband (λ_{eff} = 1621 Å), no radiation from the comet was observed, but in the U4 passband (λ_{eff} = 1537 Å), containing the wavelength of Lyman α, a bright halo 2°.3 in diameter was evident. The nucleus of the comet was about 4 arcmin in diameter, a value considerably smaller than that obtained by the Wisconsin observations of this object. This implies a radius for the nucleus of approximately 2 km at this distance from the sun.

4.4 Jupiter

Longward of 2000 Å, observations of Jupiter have been made by Wallace, Caldwell, and Savage (1972) and by Anderson, Pipes, Broadfoot, and Wallace (1969). Celescope data at 1621 Å can add to these earlier observations. At present, it has been possible to ascertain only that Jupiter has been observed at this wavelength, and that therefore it is brighter at this wavelength than expected. This adds another point to the curve of geometric albedo versus wavelength and suggests that extrapolation beyond the observations at 2000 Å would be incorrect.

The reflectivity of this planet in the ultraviolet has been interpreted to indicate that Rayleigh scattering plays an increasingly important role toward shorter wavelengths. To explain the decrease in albedo found approaching 2000 Å, absorption by some substance such as HCl or CO_2 has been suggested. However, the rise in albedo at 1600 Å observed by the Celescope Experiment cannot be explained in this manner.

4.5 Objects Surrounded by Nebulosity

Several objects known to be surrounded by nebulosity, including both reflection and emission nebulae, were observed by the Celescope Experiment. With the exception of objects in Orion, none of these is anomalously bright in the ultraviolet.

Stars observed in the Pleiades (Haramundanis, 1973b) appear to be quite normal in the ultraviolet; the reflection nebula, therefore, does not appear to contribute to their ultraviolet fluxes. Similarly, the emission nebula surrounding η Carinae does not seem to contribute to its observed flux in the ultraviolet. However, since η Carinae is an object unresolved by the Celescope photometers, its flux is difficult to interpret. HD 164492, a star in the Trifid Nebula, has a marginally bright ultraviolet flux. The Trifid, like Orion, is an emission nebula.

The star HD 270086, approximately 20 arcmin east of 30 Doradus, is extraordinarily bright in the ultraviolet. According to Henize (1956), this star is in nebulosity and is a member of the Large Cloud.

Celescope observed 22 other stars known to be associated with nebulae; none of them appears anomalously bright in the ultraviolet. If their visual and ultraviolet fluxes are augmented by scattering into the line of sight, these objects should appear brighter than normal. If the nebulosity inhibits the radiation of the star or stars from escaping, its anomalous reddening can be used to deduce the properties of the nebula. This analysis has yet to be concluded.

4.6 F Stars

Among the late-type stars observed by Celescope are 10 F stars that are much brighter in the ultraviolet than expected for their spectral class. They are listed in Table 7. We believe they represent extreme examples of F stars that have been misclassified. On the basis of their ultraviolet color indices and the assumption that they are unreddened, we have predicted their true spectral class on the main sequence. In several cases, the color indices ($m_{pg} - m_v$) appear to confirm the projected classes; however, there are insufficient accurate ground-based data to verify these estimates. UBV photometry and Hβ or Hγ photometry or classification with moderate-resolution spectra would be necessary for verification of the suggested classes.

4.7 HD 4810

This object [$\alpha_{1950} = 00^h48^m08^s$, $\delta_{1950} = +64°03'.2$, V = 8.39, (B - V) = 0.14, spectral class = A2] has large negative color excesses in both the U2 and the U3 passbands. The star was classified by Miss Cannon three times, with widely differing results: A2, A0, and A5. The ultraviolet color excesses suggest a class close to B6. However, an examination of this star on the Ross-Calvert Atlas (1934, 1936) revealed that it is in the midst of a small cluster of stars. Its ultraviolet flux is undoubtedly altered by the light of these nearby stars, although they were too faint to be recorded on the plates used in preparing the HD Catalog.

Table 7. F stars.

HD number	Spectral class	Passband	Ultraviolet color excess	m_V	m_{pg}	Color index	Predicted spectral class
6201	F5	U2	-4.14	8.7	8.4	-0.3	B3
		U3	-7.33				B5
232536	F0 (HDE)	U3	-5.45	9.4	9.9	0.5	B7
27249	F5	U2	-1.12	8.2	8.5	0.3	A5
40803	F5	U3	-4.84	8.3			A2
52242	F2	U3	-5.10	7.9			A0
69213	F0 (AI Vel)	U2	-1.12	6.6	6.4	-0.2	A3
70142	F2	U1	-1.06	8.8	7.8	-1.0	A3
73220	F8	U2	-1.39	8.6	8.2	-0.4	A7
81451	F5	U3	-5.18	8.3	8.6	0.3	A3
94464	F5	U3	-6.03	8.9	9.2	0.3	B9

4.8 Two Galactic Clusters Discovered by Celescope

During the first few orbits of Celescope operations, a number of exposures detected stars unidentifiable in the standard catalogs such as the BD. Observable on photographs, however, the stars have been identified. Of the 15 stars, otherwise unidentifiable, 4 are single stars in Carina, 3 are in Lacerta, and the rest are associated with a large dark nebula [numbered 789 in the list of Khavtasi (1955)]. Owing to their compact form and their association with the dark nebula, we suspect these last to be in two faint young galactic clusters. A program to collect UBV and Hβ photometry for these stars is under way.

5. REFERENCES

Anderson, R. C., Pipes, J. G., Broadfoot, A. L., and Wallace, L., 1969, Journ. Atmos. Sci., vol. 26, p. 874.

Becker, W., and Fenkart, R., 1971, Astron. and Astrophys. Suppl., vol. 4, p. 241.

Blaauw, A., 1963, in Basic Astronomical Data, ed. by K. Aa. Strand, vol. III of Stars and Stellar Systems, Univ. Chicago Press, Chicago, p. 383.

Blanco, V. M., Demers, S., Douglass, G. G., and Fitzgerald, M. P., 1968, Photoelectric Catalogue: Magnitudes and Colors of Stars in the U, B, V and U_c, B, V Systems, Publ. Naval Obs., 2nd ser., vol. XXI.

Bless, R. C., and Savage, B. D., 1972, in The Scientific Results from the Orbiting Astronomical Observatory (OAO-2), ed. by A. Code, NASA SP-310, p. 175.

Code, A. D., and Savage, B. D., 1972, Science, vol. 177, p. 213.

Collins, G. W. II, 1965, Astrophys. Journ., vol. 142, p. 265.

Coyne, G. V., S. J., 1972, in The Scientific Results from the Orbiting Astronomical Observatory (OAO-2), ed. by A. Code, NASA SP-310, p. 495.

Davis, R. J., 1962, Smithsonian Astrophys. Obs. Spec. Rep. No. 110.

Davis, R. J., 1968, Smithsonian Astrophys. Obs. Spec. Rep. No. 282.

Davis, R. J., Deutschman, W. A., and Haramundanis, K., 1973, Celescope Catalog of Ultraviolet Stellar Observations, Smithsonian Institution, Washington, D.C.

Dixon, W. J., and Massey, F. J., Jr., 1969, Introduction to Statistical Analysis, McGraw-Hill Book Co., New York.

Doherty, L. R., 1972, in The Scientific Results from the Orbiting Astronomical Observatory (OAO-2), ed. by A. Code, NASA SP-310, p. 411.

Fitzgerald, M. P., 1973, Astron. and Astrophys., vol. 24, p. 163.

Furenlid, I., 1970, Astrophys. Lett., vol. 7, p. 147.

Haramundanis, K., 1973a, submitted to Astrophys. Journ. (Lett.).

Haramundanis, K., 1973b, in Spectral Classification and Multicolor Photometry, Proc. IAU Symp. No. 50, ed. by J. L. Dessy, R. F. Sistero, and M. C. Sistero, D. Reidel Publ. Co., Dordrecht, Holland, in press.

Haramundanis, K., and Payne-Gaposchkin, C., 1973, Astron. Journ., vol. 78, p. 395.

Henize, K. G., 1956, Astrophys. Journ. Suppl., vol. 2, p. 315.

Hiltner, W. A., 1951, Astrophys. Journ., vol. 114, p. 241.

Houk, N., 1973, in Spectral Classification and Multicolor Photometry, Proc. IAU Symp. No. 50, ed. by J. L. Dessy, R. F. Sistero, and M. C. Sistero, D. Reidel Publ. Co., Dordrecht, Holland, in press.

Johnson, H. L., 1958, Lowell Obs. Bull. No. 90.

Johnson, H. L., 1963, in Basic Astronomical Data, ed. by K. Aa. Strand, vol. III of Stars and Stellar Systems, Univ. Chicago Press, Chicago, p. 204.

Johnson, H. M., 1972, in The Scientific Results from the Orbiting Astronomical Observatory (OAO-2), ed. by A. Code, NASA SP-310, p. 207.

Khavtasi, D. Sh., 1955, Bull. Abastumani Astrophys. Obs. No. 18.

Kurucz, R. L., Peytremann, E. and Avrett, E. H., 1973, Blanketed Model Atmospheres for Early-Type Stars, Smithsonian Institution, Washington, D. C.

Laget, M., 1973, Astrophys. Journ., vol. 180, p. 61.

Lesh, J. R., 1972, Astron. and Astrophys. Suppl., vol. 5, p. 129.

Miller, J. S., 1973, Astrophys. Journ. (Lett.), vol. 180, p. L83.

Ross, F. E., and Calvert, M. R., 1934, 1936, Atlas of the Northern Milky Way, Univ. Chicago Press, Chicago.

Schild, R. E., and Chaffee, F., 1972, in The Scientific Results from the Orbiting Astronomical Observatory (OAO-2), ed. by A. Code, NASA SP-310, p. 405.

Schmidt-Kaler, Th., 1970, in Symposium on the Spiral Structure of Our Galaxy, Proc. IAU Symp. No. 38, ed. by W. Becker and G. Contopoulos, D. Reidel Publ. Co., Dordrecht, Holland, p. 284.

Serkowski, K., 1963, Astrophys. Journ., vol. 138, p. 1046.

Sharpless, S., 1952, Astrophys. Journ., vol. 116, p. 251.

Shklovsky, I. S., 1953, Doklady Akad. Nauk U.S.S.R., vol. 90, p. 983.

Smith, L. F., 1968, in Wolf-Rayet Stars, Nat. Bureau Standards Spec. Publ. 307, p. 21.

Walborn, N. R., 1971, Astrophys. Journ. Suppl. No. 198, vol. 23, p. 257.

Wallace, L., Caldwell, J. J., and Savage, B. D., 1972, in The Scientific Results from the Orbiting Astronomical Observatory (OAO-2), ed. by A. Code, NASA SP-310, p. 115.

Woltjer, L., 1957, Bull. Astron. Netherlands, vol. 14, p. 39.